

As power requirements build to the 1- to 10-megawatt level for future space and lunar base missions, however, it is likely that either the bus voltage must leap to the kilovolt level or current levels must increase with paralleling and phase control. In either case, new semiconductors and other components and more switchgear, cabling, and connectors will be required. Designs for operating in the lunar environment, where dust may provide severe environmental interactions, will be especially critical. Early research into all these types of hardware is warranted. We envision that both ac and dc equipment of various types and voltage levels will be routinely used in orbit and on planetary surfaces.

As in the previous cases, it is unlikely that nonterrestrial resources will affect power management and distribution

systems by 2010. Rather, it is the power system that will enable utilization of nonterrestrial resources.

Nuclear Energy Technology

David Buden

Radioisotope Generators

Current status: Radioisotope generators use the spontaneous decay of plutonium-238 as a heat source. The energy has traditionally been converted to electricity by means of thermocouples placed next to the heat source. (See figure 24.) Radioisotope generators have been launched in 21 spacecraft, beginning with the successful flight of a space nuclear auxiliary power (SNAP-3A) source in 1961. A summary of launches is shown in table 1.

S3-73

140708
P-25

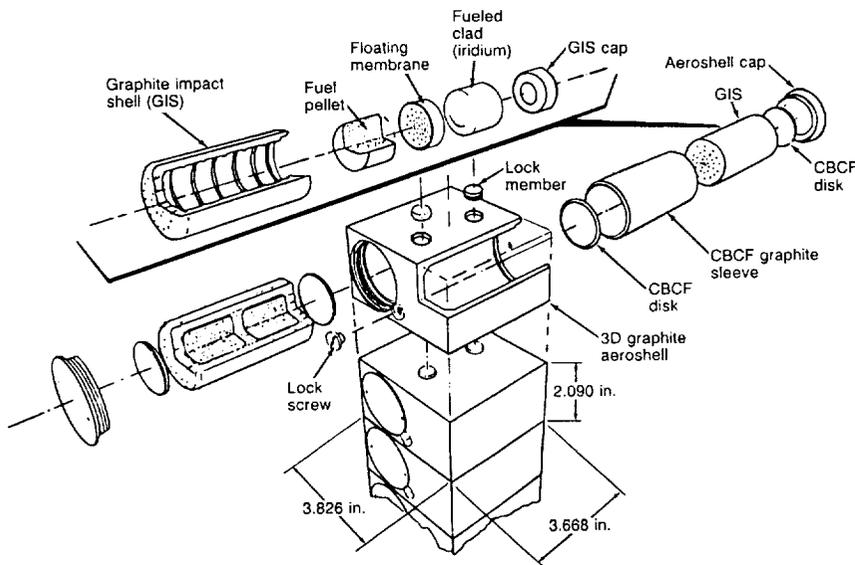
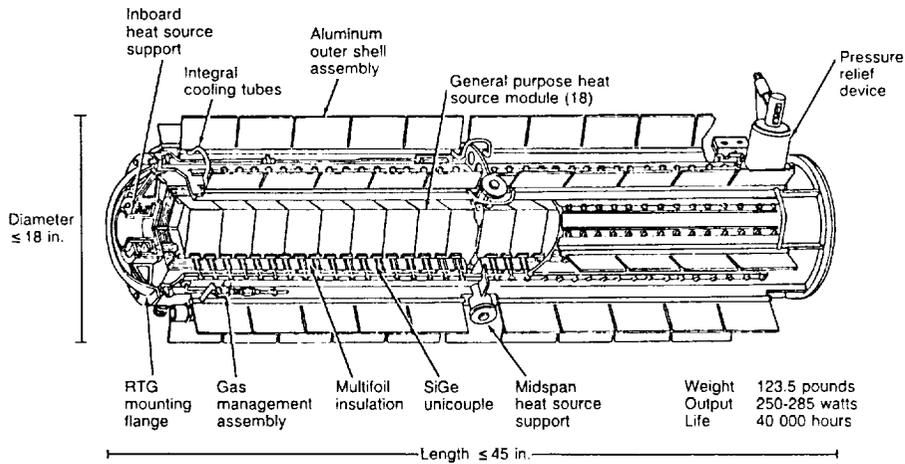


Figure 24

Radioisotope Thermoelectric Generator

This radioisotope thermoelectric generator (RTG) has been built to power the instruments to study Jupiter on the Galileo mission and the poles of the Sun on the Ulysses mission. The plutonium oxide in its 18 general purpose heat source (GPHS) modules decays to heat one end of a silicon-germanium unicouple. The difference in temperature on the two ends of this thermocouple creates an electric current. The detail shows how the pellets of nuclear fuel are clad first in iridium, then in graphite.

TABLE 1. Summary of Space Nuclear Power Sources Launched by the United States (1961-1980)

Power source ^a	Spacecraft	Mission type	Launch date	Status
SNAP 3A	Transit 4A	Navigational	June 29, 1961	Successfully achieved orbit
SNAP 3A	Transit 4B	Navigational	Nov. 15, 1961	Successfully achieved orbit
SNAP 9A	Transit 5BN-1	Navigational	Sept. 28, 1963	Successfully achieved orbit
SNAP 9A	Transit 5BN-2	Navigational	Dec. 5, 1963	Successfully achieved orbit
SNAP 9A	Transit 5BN-3	Navigational	Apr. 21, 1964	Mission aborted; burned up on reentry
SNAP 10A	Snapshot	Experimental	Apr. 3, 1965	Successfully achieved orbit
SNAP 19B2	Nimbus B-1	Meteorological	May 18, 1968	Mission aborted; heat source retrieved
SNAP 19B3	Nimbus III	Meteorological	Apr. 14, 1969	Successfully achieved orbit
SNAP 27	Apollo 12	Lunar	Nov. 14, 1969	Successfully placed on lunar surface
SNAP 27	Apollo 13	Lunar	Apr. 11, 1970	Mission aborted on way to Moon; heat source returned to South Pacific Ocean
SNAP 27	Apollo 14	Lunar	Jan. 31, 1971	Successfully placed on lunar surface
SNAP 27	Apollo 15	Lunar	July 26, 1971	Successfully placed on lunar surface
SNAP 19	Pioneer 10	Planetary	Mar. 2, 1972	Successfully operated to Jupiter & beyond
SNAP 27	Apollo 16	Lunar	Apr. 16, 1972	Successfully placed on lunar surface
Transit-RTG	"Transit" (TRIAD-01-1X)	Navigational	Sept. 2, 1972	Successfully achieved orbit
SNAP 19	Pioneer 11	Planetary	Apr. 5, 1973	Successfully operated to Jupiter & Saturn & beyond
SNAP 19	Viking 1	Mars	Aug. 20, 1975	Successfully landed on Mars
SNAP 19	Viking 2	Mars	Sept. 9, 1975	Successfully landed on Mars
MHW	LES 8/9 ^b	Communications	Mar. 14, 1976	Successfully achieved orbit
MHW	Voyager 2	Planetary	Aug. 20, 1977	Successfully operated to Jupiter & Saturn & beyond
MHW	Voyager 1	Planetary	Sept. 5, 1977	Successfully operated to Jupiter & Saturn & beyond

^aSNAP 10A was powered by a nuclear reactor; the remainder were powered by radioisotope thermoelectric generators.
^bLES = Lincoln experimental satellite.

The technical characteristics of these radioisotope generators are listed in table 2. Their reliability and long life is demonstrated by the Pioneer satellite, which after 11 years of operation left our solar system still functioning. The recent magnificent pictures of Saturn taken from the Voyager spacecraft powered by radioisotope generators are also testimonials to the

longevity and reliability of this type of power supply. (See figure 25.)

Radioisotope thermoelectric generators (RTGs) have been used where long life, high reliability, solar independence, and operation in severe environments are critical. Economic considerations have restrained them from more general use.

TABLE 2. *Radioisotope Generator Characteristics*

	SNAP 3A	SNAP 9A	SNAP 19	SNAP 27	Transit-RTG	MHW	GPHS-RTG	DIPS
Mission	Transit	Transit	Nimbus Pioneer Viking	Apollo	Transit	LES 8/9 Voyager	Galileo	
Fuel form	Pu metal	Pu metal	PuO ₂ -Mo cermet	PuO ₂ microspheres	PuO ₂ -Mo cermet	Pressed PuO ₂	Pressed PuO ₂	Pressed PuO ₂
Thermoelectric material	PbTe	PbTe	PbTe-TAGS	PbSnTe	PbTe	SiGe	SiGe	Organic Rankine
BOL output power watts (e)	2.7	26.8	28-43	63.5	36.8	150	290	1300
Mass, kg	2.1	2.2	13.6	30.8 ^a	13.5	38.5	54.4	215
Specific power, W _e /kg	1.3	2.2	2.1-3.0	3.2 ^b	2.6	4.2	5.2	6.0
Conversion efficiency, %	5.1	5.1	4.5-6.2	5.0	4.2	6.6	6.6	18.1
BOL fuel inventory watts (t)	52	565	645	1480	850	2400	4400	7200
Fuel quantity, curies	1800	17 000	34 400- 80 000	44 500	25 500	7.7 x 10 ⁴	1.3 x 10 ⁵	2.1 x 10 ⁵

^aWithout cask.

^bIncludes 11.1-kg cask.

RTG = radioisotope thermoelectric generator

GPHS = general purpose heat source

DIPS = dynamic isotope power system

TAGS = telluride antimony germanium silver

BOL = beginning-of-life

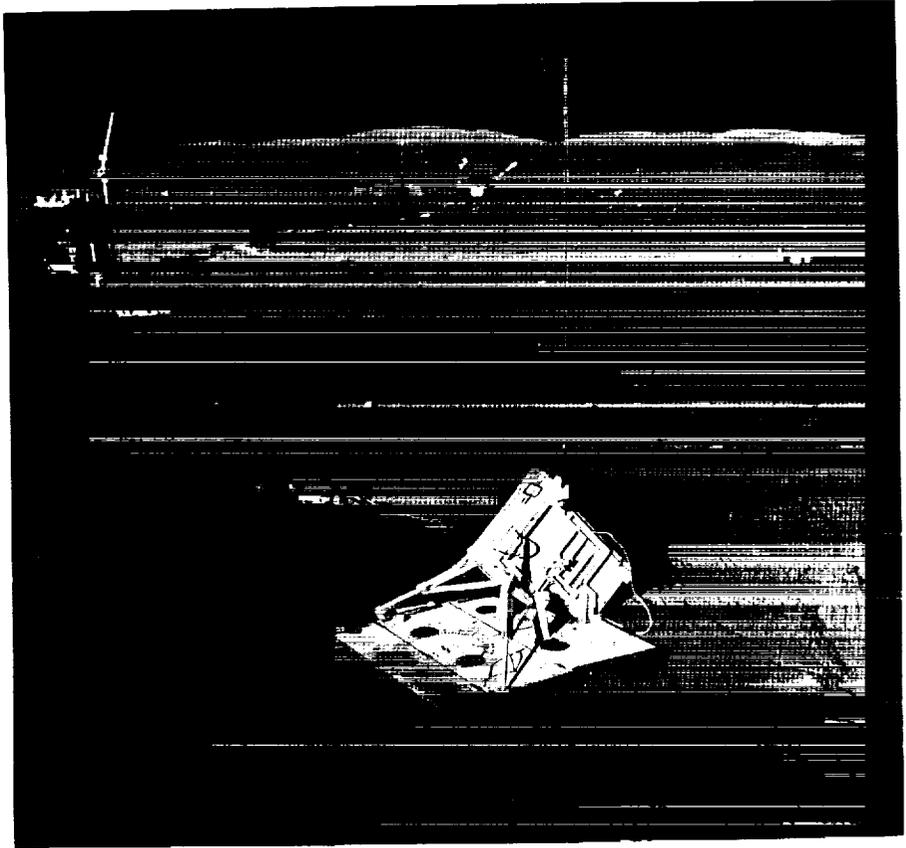
Figure 25

**Experiments and Spacecraft
Powered by RTGs**

A number of scientific experiments
and spacecraft have been powered
by radioisotope thermal generators
(RTGs).

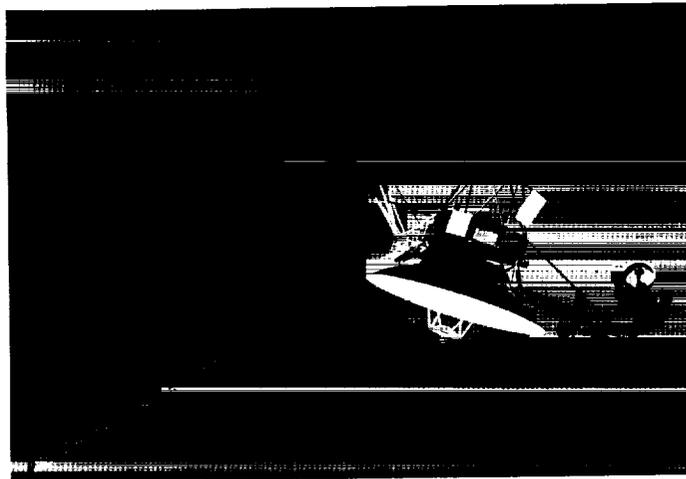
**a. Apollo Lunar Surface Experiments
Package (ALSEP)**

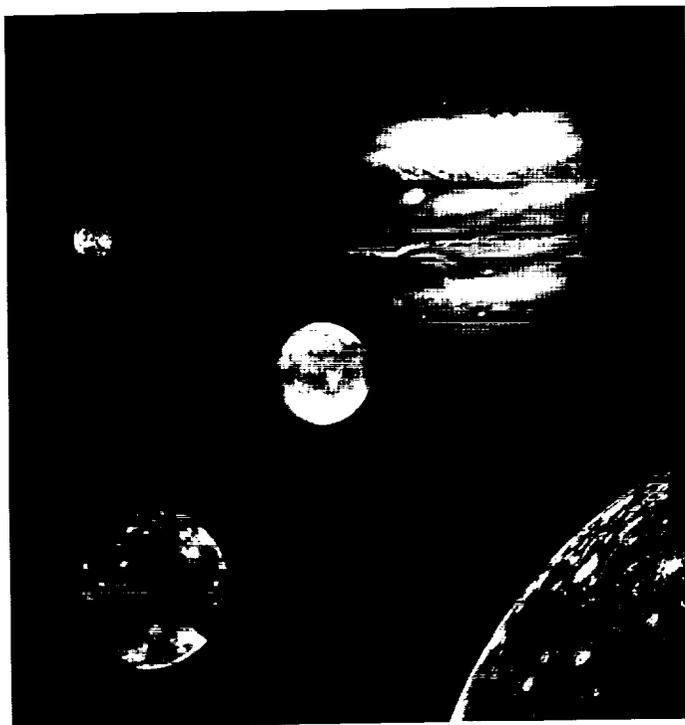
The Apollo missions included lunar
surface experiments powered by
RTGs. One of them, a seismic mortar,
is shown in the foreground of this
photo connected by cables to the
central control and communications
unit in the background. The whole
package of experiments was powered
by the finned RTG, which appears
to the right of the control and
communications unit. The RTG units
proved reliable and powered the
instruments left on the surface of
the Moon for years after the astronauts
returned. These nuclear power
generators also proved safe; one even
survived the reentry of the Apollo 13
Lunar Module (LM).



b. Voyager

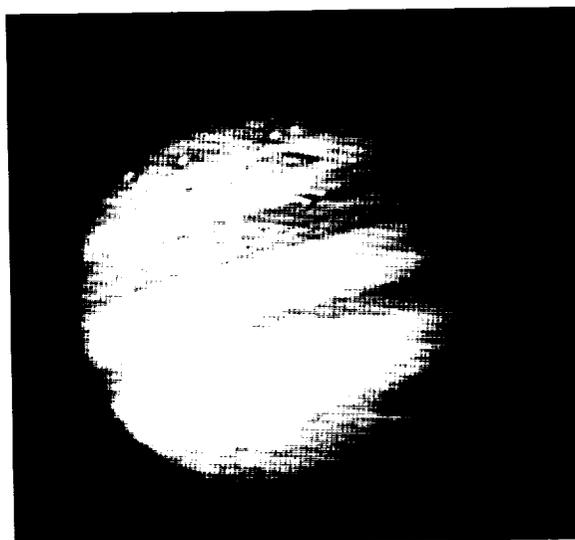
RTG units were also used to power the
Voyager spacecraft to Jupiter, Saturn,
and the outer planets.





c. Jupiter and Its Moons

This composite photograph shows the moons of Jupiter, not to scale but in their relative positions: Io (upper left), Europa (center), Ganymede (lower left), and Callisto (lower right).

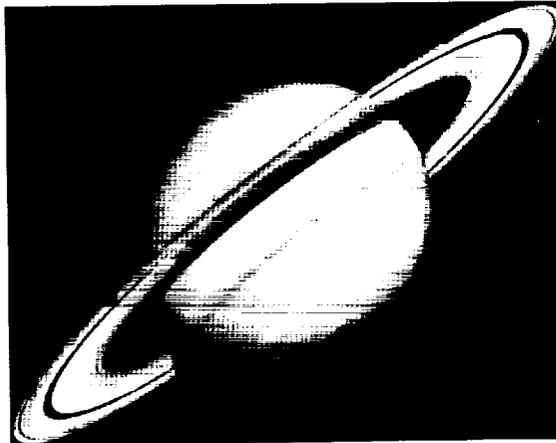


d. Io Moving Across the Face of Jupiter

In this dramatic view captured by Voyager 1's camera, the moon Io can be seen traveling across the face of Jupiter and casting a shadow on the giant planet.

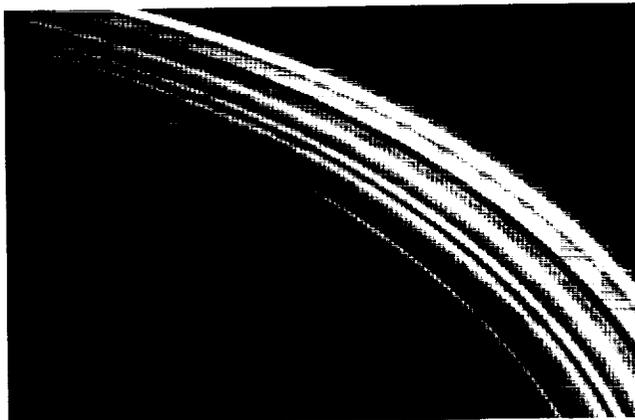
e. Saturn

Saturn was also photographed by Voyager using RTG power. Here is a full view of the second largest planet and its ring system.



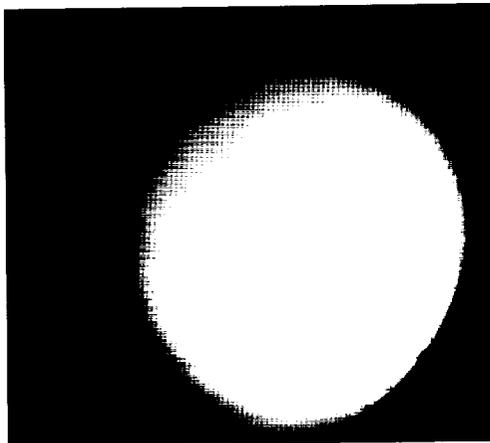
f. The Rings of Saturn

Voyager revealed for the first time a faint ring of particles around Jupiter and provided closeups of the well-known rings of Saturn, showing details of the intricate structure of these rings.



g. Uranus

Uranus also was photographed by the RTG-powered Voyager 2 in 1986.



Future developments: Improved versions of the RTG will have better performance. However, RTGs will probably be restricted to under 500 W. Higher power levels of maybe 5-10 kW_e are possible by using dynamic converters for power conversion. A 1.3-kW_e version was tested for several thousand hours before the program was terminated. A revised program to cover the 1-10 kW_e range is scheduled to start in 1988. These improved versions using thermocouples and dynamic converters could be used for lunar and Mars rovers and explorations away from lunar camps and bases.

Nuclear Reactor Power Plants

Current status: The current U.S. effort to develop nuclear reactors for space is centered in a program entitled "SP-100," which is a joint program of the Department of Defense, the Department of Energy, and NASA. (SP-100 is not an acronym.)

The decision to proceed with the construction of a specific space nuclear power plant was made and a contractor selected in 1986. The program has completed the critical technology development and assessment phase. Activities centered around evaluating promising space reactor concepts and determining which technologies are most likely to achieve the required performance levels. The technology assessment and development phase included defining mission requirements, doing conceptual designs of possible systems, and researching and developing critical technologies.

Following screening by the SP-100 Program of over a hundred potential space nuclear power system concepts, the field was narrowed to three candidate systems which appear to meet the requirements in table 3 without unreasonable technical risks or development time.

One concept uses a fast-spectrum, lithium-cooled, cylindrical, pin-type-fuel-element reactor with thermocouples for power conversion (fig. 26) (General Electric Co. 1983). The system is made up of a 12-sided cone structure with a 17-degree cone half angle. The reactor, which is a right-circular cylinder approximately 1 meter in diameter and 1 meter

high, is at the apex of the conical structure. It is controlled by 12 rotatable drums, each with a section of absorbing material and a section of reflective material to control the criticality level. Control of the reactor is maintained by properly positioning the drums. The reactor outlet temperature is 1350 K.

TABLE 3. SP-100 Goals

Performance	
Power output, net to user, kW _e	100
Output variable up to 100 kW _e	
Full power operation, years	7
System life, years	10
Reliability	
1st system, 2 years	0.95
Growth system, 7 years	0.95
Multiple restarts	
Physical constraints	
Mass, kg	3000
Size, length within STS envelope, m	6.1
Interfaces	
Reactor-induced radiation after 7 years' operation, 25 m from forward end of reactor	
Neutron fluence, n/cm ²	10 ¹³
Gamma dose, rads	5 x 10 ⁵
Mechanical	STS launch conditions
Safety	Nuclear Safety Criteria and Specifications for Space Nuclear Reactors

The shield is mounted directly behind the reactor and consists of both a gamma and a neutron shield. The gamma shield consists of multiple layers of tungsten designed so as to prevent warping. The neutron shield is made up of a series of axial sections with thermal conductors between them. The thermal conductor carries the gamma- and neutron-generated heat to the shield surface, where it is radiated to space. Anticipated temperature levels are 675 K, maximum.

Thermal transport is accomplished by thermoelectrically driven

electromagnetic pumps. The thermocouples for the pumps are powered by the temperature drop between the working fluid and the pump radiators. This approach assures pumping of the working fluid as long as the reactor is at temperature, and it facilitates the cooldown of the reactor when power is no longer required.

The reactor's thermal interface with the heat distribution system is through a set of heat exchangers. In this way, the reactor system is self-contained, can be fabricated and tested at a remote facility, and can be mated to the power system

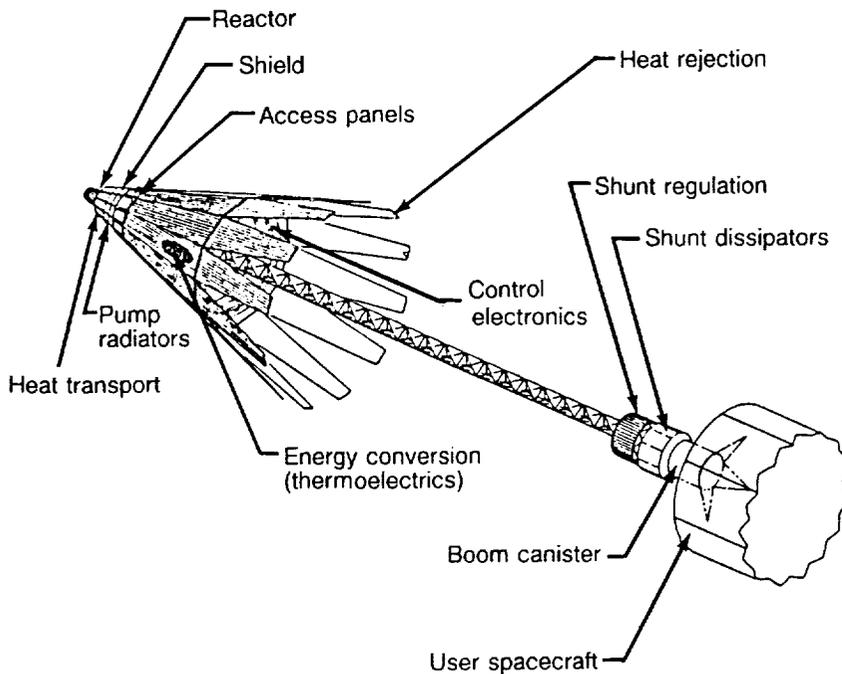


Figure 26

Concept of High-Temperature Reactor With Thermoelectric Power Conversion

downstream. Access panels are provided on the main body to facilitate the connection of the heat distribution system to the heat exchanger.

Thermoelectric elements for converting thermal energy to electric power are bonded to the internal surfaces of the heat rejection panels and accept heat from the source heat pipe assembly.

The heat rejection surfaces are beryllium sheets with titanium-potassium heat pipes brazed to the surface to distribute and carry the heat to the deployable panels, which are needed for additional heat rejection. The deployable panels are thermally coupled

through a heat-pipe-to-heat-pipe thermal joint, which is very similar to the source-heat-pipe-to-heat-exchanger joint, made integral by the use of special materials that are self-brazing in orbit. To allow the deployment of the panels, a bellows-like heat pipe section is mounted at the tail end of the heat pipes on the fixed panel. Such a flexible heat pipe has been demonstrated.

The system has a wide range of flexibility. Its output can be expanded either by increasing the thermoelectric efficiency or by increasing the size and weight of the system. The potential for scaling up the system is shown in figure 27 (Katucki et al. 1984).

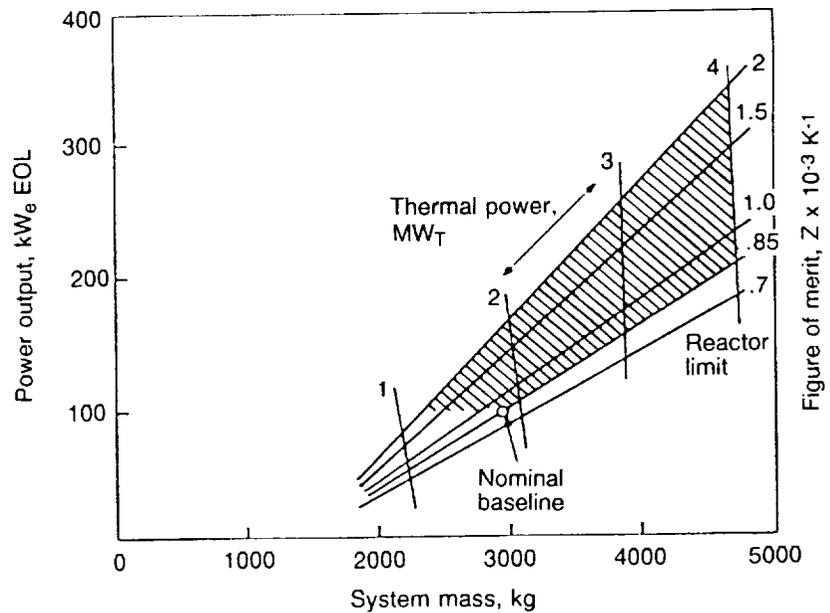


Figure 27

Scalability of Concept of High-Temperature Reactor With Thermoelectric Conversion

A second approach evaluated is an in-core thermionic system with a pumped sodium-potassium eutectic coolant (GA Technologies and Martin Marietta 1983). The general arrangement of this space power system design is shown in figure 28. The design forms a conical frustum that is 5.8 m long, with major and minor diameters of 3.6 m and 0.7 m. The reactor-converter subsystem includes the reactor, the reflector/control drums, and the neutron shield. The reactor contains the thermionic

fuel element (TFE) converters within a cylindrical vessel, which is completely surrounded by control drums.

The hot NaK leaves the reactor at the aft end and the cold NaK is returned to the forward end, thus minimizing differential thermal expansion in the piping. The reactor is also surrounded by an array of long, thin cylindrical reservoirs that collect and retain the fission gases generated in the reactor core during the operating

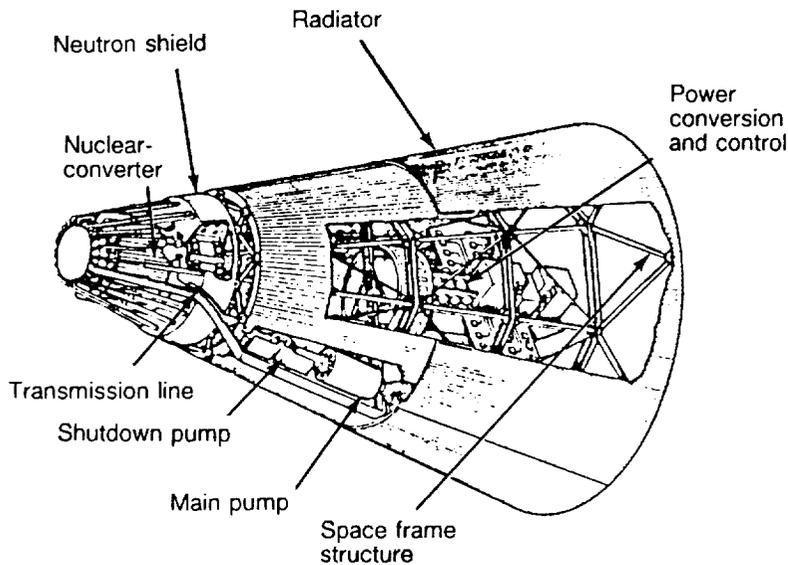


Figure 28

Concept of In-Core Thermionic Power Plant

life of the system. Waste heat is removed from the primary loop through the heat exchanger. The energy is transferred through the heat-sink heat exchanger to heat pipes that form the radiating surfaces for rejection of heat to space.

Within the reactor vessel are 176 TFEs, a grid plate to support the TFEs at one end, a tungsten gamma shield, and the eutectic NaK coolant. Each TFE is welded into the flattop head of the vessel but allowed to move axially in the grid plate. Expansion is expected to be small, since the TFE sheath tubes and reactor vessel are both made of an alloy of niobium and

1 percent zirconium and their temperatures are nearly the same.

The TFE consists of six cells connected in series with end reflectors of beryllium oxide. Boron carbide neutron absorber is placed at both ends of the fuel element to reduce the thermal neutron flux in the coolant plenums and in the gamma and neutron shields. This reduces activation of the coolant, secondary gamma ray production, and nuclear heating of the lithium hydride shield.

The individual cells (see fig. 29) are connected in series to build up voltage from the 0.4-V cell output. Electrical power is generated in

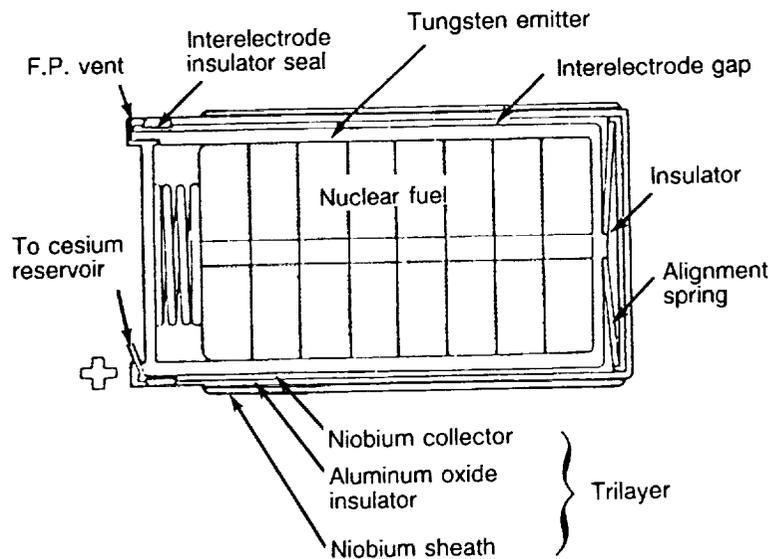


Figure 29

In-Core Thermionic Converter

the space between the tungsten emitter and the niobium collector, and the electrical current output is conducted from one cell to the next through the tungsten stem of the emitter and the tantalum transition piece. The UO_2 fuel is held in place and supported during launch by a retention device designed to retract when the fuel expands upon heating. The alignment spring at the base of the emitter centers the emitter in the collector to maintain a uniform interelectrode spacing. It also restrains the emitter against launch vibration to prevent large displacements and limit stresses in the thin stem at the other end of the emitter.

Fission gases are vented from the UO_2 fuel to prevent the buildup of pressures that would cause creep deformation of the tungsten emitter and close the interelectrode space. Fission gases are kept separate from the cesium (used to reduce the space charge effect) by the ceramic-to-metal seal and the arrangement of passages through the emitter cap and transition piece.

Reactor control is provided by the rotation of the 20 cylindrical control drums surrounding the

reactor. The heat transport subsystem is a single loop that includes all of the NaK plumbing aft of the reactor, the heat-sink heat exchanger, and the radiator. The 100-mm-diameter NaK lines to and from the reactor are routed inside helical grooves in the outer surface of the neutron shield and then pass along the inside surface of the radiator to connect to the heat-sink heat exchanger. The configuration of the NaK lines along the shield is helical, rather than straight, to avoid degradation of the shield performance due to neutron streaming in the pipe channels.

The helical channels in the shield are also occupied by the electrical transmission lines, which are flattened in cross section and are routed over the NaK lines to serve as meteoroid protection. Electromagnetic pumping is used to circulate the NaK during normal operation and during shutdown. Two electromagnetic pumps are provided in the cold leg of the NaK circuit: an annular linear-induction pump to serve as the main pump and a parallel thermoelectromagnetic pump (with a check valve) to provide shutdown pumping capability.

The radiator contains two finned heat pipe assemblies, which form a conical frustum when the panels are assembled on the radiator structure. The heat pipes follow the slant height of the core and are deployed fore and aft of the heat-sink heat exchanger, to which they are thermally coupled. The radiator provides environmental protection for the equipment it houses.

Growth is possible by either redesigning the reactor with more TFEs or increasing the emitter temperature (see fig. 30) (Katucki et al. 1984). An upper temperature level of about 2000 K is believed to be an operational limit for the tungsten emitter.

The third approach uses a Stirling engine to convert to electricity heat from a lower temperature (900 K), fuel-pin-type reactor. This design emphasizes the use of

state-of-the-art fuel pins of stainless steel and UO_2 , with sodium as the working fluid. Such fuel pins have been developed for the breeder reactor program, with 1059 days of operation and 8.5-percent burnup demonstrated.

The reactor can be similar in design to the high-temperature reactor, but it utilizes lower temperature materials. In figure 31 (General Electric Co. 1983), the reactor is constructed as a separate module from the conversion subsystem. Four Stirling engines, each rated to deliver 33 kW_e , are included in the design concept to provide redundancy in case of a unit failure. Normally the engines operate at 75 percent of rated power to produce an output of 100 kW_e . Each engine contains a pair of opposed-motion pistons, which operate 180 degrees out of phase. This arrangement eliminates unbalanced linear

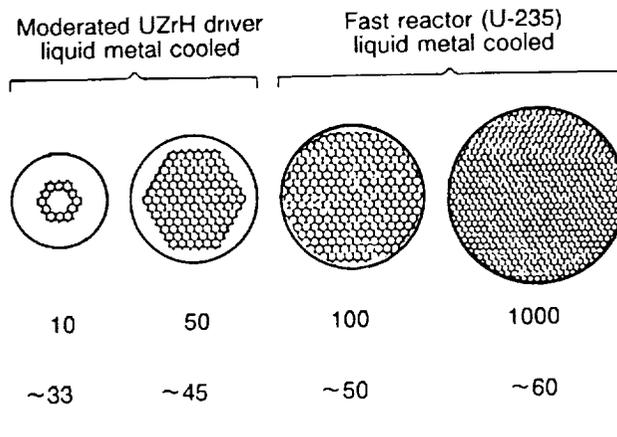


Figure 30

Scalability of In-Core Thermionic Reactor

momentum. Each engine receives heat from a pumped loop connected to the reactor vessel.

An alternate arrangement would deliver the heat through an interface heat exchanger with heat pipes between the heat exchanger and the engine. Waste heat is removed from the cooler heads and delivered to a liquid-to-heat-pipe heat exchanger. The heat pipes, in turn, deliver the waste heat to the radiator where it is rejected to space.

Figure 32 provides performance curves for the Stirling system. A low temperature will meet the goal of 100 kW_e. However, growth systems favor combining the Stirling engines with higher temperature reactors both to minimize mass and to reduce heat rejection surface areas.

Figure 33 summarizes the mass and specific power projected for the 100-kW_e class of power plants.

The fast-spectrum, lithium-cooled reactor with thermoelectrics (concept 1) has been selected for the ground demonstration system. Work is continuing on thermionic fuel element development and Stirling engine development for possible use in growth versions of SP-100.

Future developments: Several classes of reactor power plants will be needed in the future to provide adequate energy for lunar camps and base stations, the growth space station and Space Station 2, and electric propulsion. The 50- to 1000-kW_e power plant being developed by the SP-100 Program for flight in the early to mid-1990s will meet the power

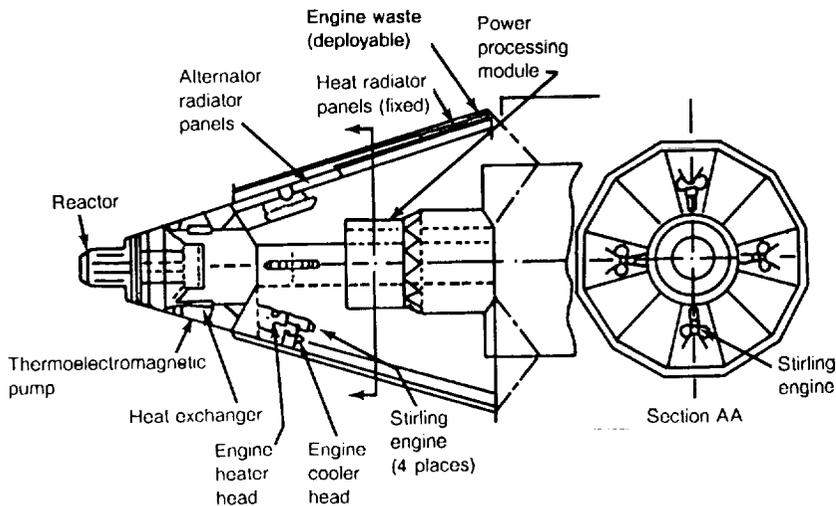


Figure 31

Concept of Stirling Engine Conversion

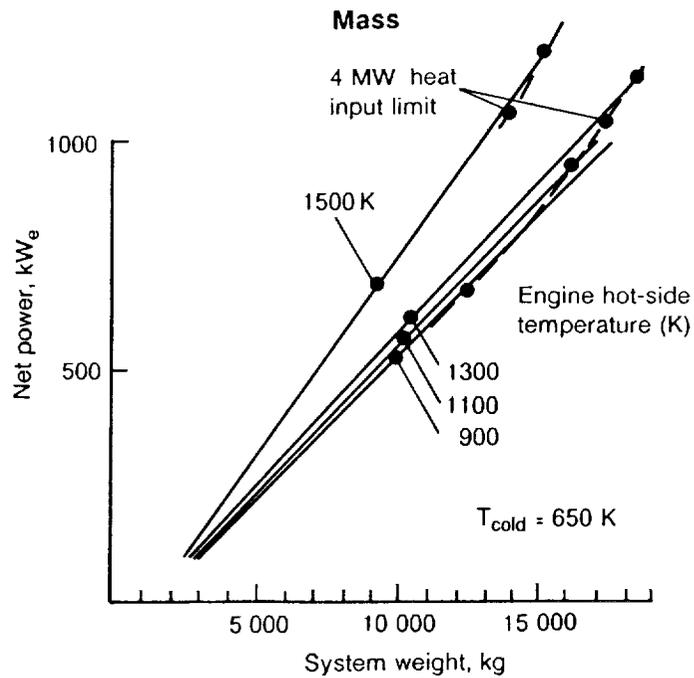
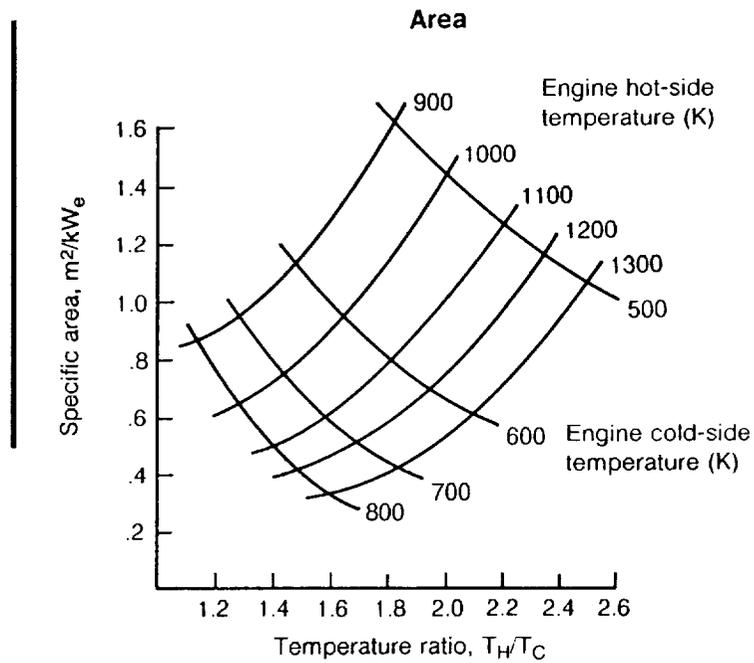


Figure 32

Scalability of Stirling Power System Concept

requirements of the growth space station, the lunar surface day/night camp, and nuclear electric propulsion. However, the requirements and designs have been aimed at unmanned systems. These should be reviewed and modified as necessary to meet manned operational requirements. These requirements could include shielding that completely encloses the reactor, additional emphasis on shutdown heat removal and safety systems that are

independent and redundant, and considerations of maintainability and disposal.

We anticipate that the early lunar camps and bases will involve the transport of a space station version of the 100-kW_e-class power plant with little shielding. The power plant would be arranged to reject heat to space. People would be protected by using lunar materials for the radiation barrier.

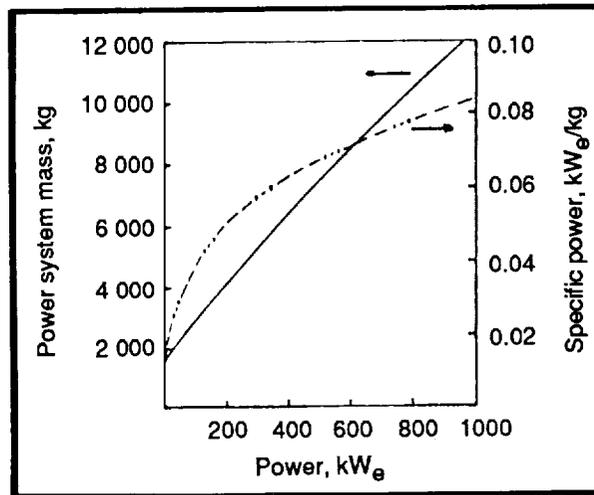


Figure 33

Performance Projections for Space Nuclear Reactor Power System

Space Station 2, requiring 1-10 MW_e , would need a new class of reactor plants. Major changes in reactor designs may be called for, such as higher temperatures, refuelability, and maintainability of certain components. Significant improvements in power conversion and heat rejection are also necessary. The power conversion will probably work at a higher temperature; innovative design through in-core thermionics is being evaluated as an alternative. Heat rejection will need a deployable system that uses a

nonarmored radiator technology. One concept, the liquid droplet radiator, is now being pursued to demonstrate technology feasibility. Other concepts include belts, balloons, and rollup heat pipes. The goal would be to package a 10- MW_e power plant in a single Shuttle launch.

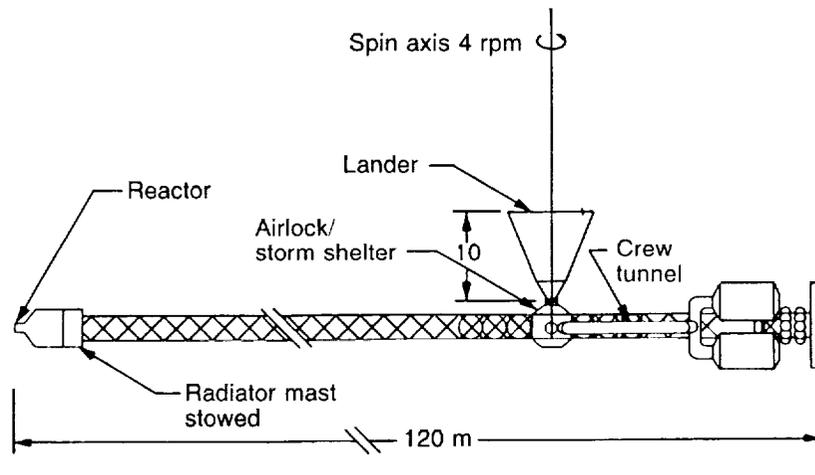
The power plant for Space Station 2 can meet the requirements for a manned Mars mission (fig. 34) and for a lunar orbital transfer vehicle using nuclear electric propulsion. For the advanced lunar base, the same power plant could be

Figure 34

Manned Mars Mission

After a 600-day flight to Mars, a 100-day reconnaissance phase is initiated, during which a crew will land and investigate Mars for 1 month. The return trip to geosynchronous Earth orbit (GEO) takes about a year.

Using this configuration and conducting a mission of this sort would require 6 MW of power operating for 14×10^3 hours and thus expending an energy total of 8×10^7 kWhr.



used. Again, lunar soil could provide shielding. However, if a mining and materials fabrication capability were in place, it could be used to fabricate a specially designed heat rejection subsystem. Doing so could produce a major savings in mass transfer from Earth. Several innovative designs are possible, such as continuous ejection and collection of fluid or solid particles.

Public Safety and the Use of Nuclear Reactors in Space

Policy and goals: The policy of the United States for all U.S. nuclear power sources used in space is to ensure that the probability of release of radioactive materials and the amounts released are such that an undue risk is not presented, considering the benefits of the mission (U.S. Department of Energy 1982). Safety criteria are specified for the design of the SP-100 space nuclear reactor power plant;

safety is to be built into the design, not just added on.

The restriction of radiation exposure (DOE 1982) depends on reducing the probability of an accident that might release radioactive materials into the environment and on limiting the magnitude of such a release should one occur.

Space nuclear power applications must keep the radiation exposure of astronauts, occupational workers (e.g., ground support personnel), and members of the general public "as low as reasonably achievable" during all mission phases, normal and abnormal. According to recommended standards (U.N. General Assembly paper 1980), the maximum accumulated doses for closely involved workers and for the general population are those listed in table 4. Allowable doses for astronauts are generally in the same range as those allowed for radiation workers.

TABLE 4. Normal Mission Exposure Limits

Type of exposure	Condition	Dose, rem
Individuals in controlled area:		
Whole body, head and trunk, active blood-forming organs, gonads, or lens of eye	Accumulated dose	5(N-18)*
	Calendar quarter	3
Skin, thyroid, and bone	Year	30
	Calendar quarter	10
Hands and forearms, feet and ankles	Year	75
	Calendar quarter	25
Other organs	Year	15
	Calendar quarter	5
Individuals in uncontrolled areas:		
Whole body, gonads, or bone marrow	Annual dose to critical individuals at points of maximum probable exposure	0.5
Other organs	Same	1.5
Whole body, gonads, or bone marrow	Average annual dose to a suitable sample of the exposed population	0.17
Other organs	Same	0.5

* Where N equals age in years at next birthday

rem or "roentgen equivalent man" = the dose which produces an equivalent probability of harmful radiation effects

1 rem = 1 cSv

The safety program is designed to protect the public against exposure to radiation levels above established standards. This can be accomplished by preventing accidental reactor criticality and by avoiding release of radioactive byproducts into the biosphere in sizes and concentrations that exceed the standards.

Another set of safety goals encompasses the protection of

investments in facilities both on the ground and in space. These facilities must be protected both because they are national assets that would be costly to replace and because a failure would produce significant delays in our national efforts to build the space station. Safety goals and requirements are summarized in table 5.

TABLE 5. *Safety Goals and Requirements*

Goals	Reasons	Design requirements
Assure the existence of normal conditions before launch to avoid special handling or precautions.	To protect workers and astronauts	<p>The reactor shall not be operated (except for zero power testing) until a stable orbit or flight path is achieved.</p> <p>There must be two independent systems to reduce reactivity to a subcritical state.</p> <p>Unirradiated fuel shall pose no significant environmental hazard.</p>
Prevent inadvertent criticality.	<p>To ensure that the public is not exposed to levels of radiation that exceed standards</p> <p>To protect the Shuttle crew</p>	<p>The reactor must remain subcritical if immersed in water or another fluid.</p> <p>The reactor must have a significant negative power coefficient.</p> <p>The reactor must be subcritical in an Earth-impact accident.</p> <p>A reactor safety system must be incorporated.</p> <p>There must be quality assurance standards.</p> <p>A positive-coded telemetry system must be used for reactor startup.</p> <p>There must be redundant control and safety systems.</p> <p>There must be independent sources of electrical power for the reactor control system, the reactor protection system, and the reactor communication system.</p> <p>There must be instrumentation to continuously monitor reactor status.</p>
Avoid release of radioactive byproducts in concentrations exceeding radiological standards.	To ensure that the public is not exposed to radiation levels that exceed standards and to protect the biosphere against concentration of radioactive elements above safety standards	<p>An orbital boost system must be provided for short-lived orbits.</p> <p>There must be spacecraft attitude controllers for the communication and boost systems.</p>
Avoid unplanned core destruction.	To protect space investments and to avoid contamination of volumes of the space environment	<p>An independent system for decay heat removal must be provided for shutdown situations.</p> <p>There must be two independent systems to reduce reactivity to a subcritical state.</p> <p>A positive-coded signal must be used to operate the reactor.</p> <p>There must be two independent reactor protection systems.</p> <p>Fault-detection systems must be provided for the reactor protection systems.</p>

The safety review process: The United States requires an analysis of each space mission involving nuclear material to assess the potential radiological risk to the biosphere. The process begins when the space mission is defined and the design is conceived. The safety review process continues through launch safety analysis, approval to launch, and proper nuclear power source disposal.

The developer of the nuclear power source is responsible for performing the nuclear safety analyses for the system. Results of these safety analyses are reported at least three times during the development cycle in documents entitled Preliminary Safety Analysis Report (PSAR), Updated Safety Analysis Report (USAR), and Final Safety Analysis Report (FSAR).

The Preliminary Safety Analysis Report is issued 120 days after a design concept is selected. It contains a description of the design, a failure mode analysis, and a nuclear safety analysis. The latter two requirements are based on the safety research data for the

development of heat sources, historical heat source design information, and the requirements set forth in the guidelines written by the Department of Energy (DOE). At this stage of system development, the failure mode analysis is based on the response to potential accident environments and on design limitations established by the guidelines.

The Updated Safety Analysis Report is issued 90 days after the design is set. It is similar in format to the preliminary report. Additional requirements include a description of the mission on which the system is to be used and an update of the failure mode analysis using data from the developmental tests performed to set the design.

The Final Safety Analysis Report is issued approximately 1 year before the scheduled launch and is similar in format to the earlier reports. This report provides final system, mission, and safety assessment data, factoring in the results of the verification and qualification test programs. Thus, the final assessment is based on the actual mission environments.

The Interagency Nuclear Safety Review Panel (INSRP) is responsible for review of the safety analysis reports at each step of the development process. The end result of the INSRP process is the Safety Evaluation Report (SER). This report evaluates potential human exposures to radiation and the probabilities of exposure during all phases of the mission. The INSRP submits the Safety Evaluation Report to the heads of the Department of Energy, NASA, and the Department of Defense for their review. The head of the agency that wants to fly the nuclear power source must then

request launch approval from the President through the Office of Science and Technology Policy. The ultimate authority for launch and use of the nuclear power source lies with the President of the United States.

Figure 35 shows the generalized sequence of events in this flight safety evaluation process. Because safety features are designed into U.S. nuclear power sources from the very beginning, this safety review process is actually an integral part of the overall flight system development.

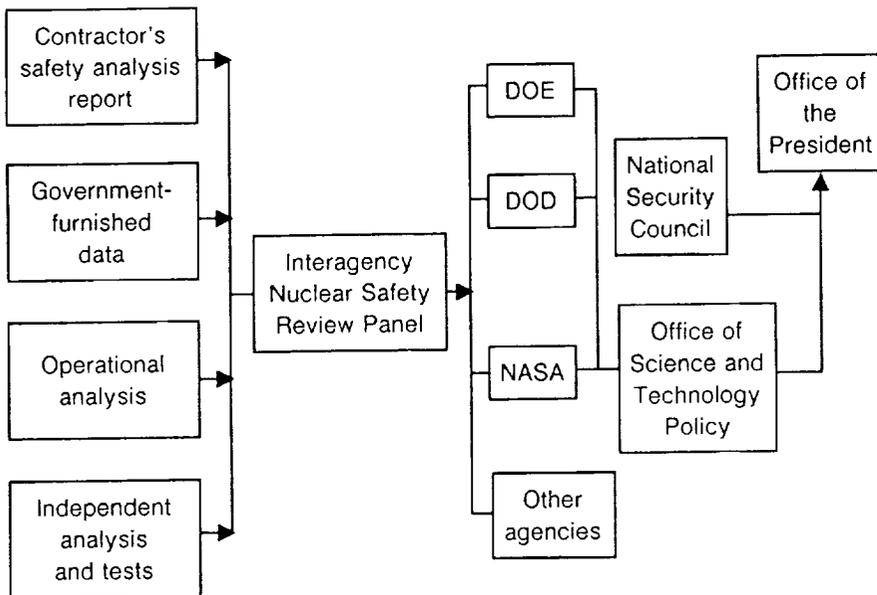


Figure 35

U.S. Safety Review and Launch Approval Process

References

GA Technologies and Martin Marietta. 1983. Conceptual Design Studies in Support of the SP-100 Program. Report No. GA-C17354, LaJolla, CA, Dec. 9.

General Electric Co. 1983. SP-100 Conceptual Design Study. Doc. No. 835SDS4262, Valley Forge, PA, Dec. 7.

Katucki, R.; A. Josloff; A. Kirpech; and F. Florio. 1984. Evolution of Systems Concepts for a 100-kW_e-Class Space Nuclear Power System. Proc. 1st Symp. on Space Nuclear Power Systems, Univ. of New Mexico, pp. 149-164.

U.N. General Assembly. 1980. Questions Relating to the Use of Nuclear Power Sources in Outer Space. See U.S. working paper Studies on Technical Aspects and Safety Measures of Nuclear Power Sources in Outer Space. A/AC.105/C.1/WG.V/L.8, Jan. 25.

U.S. Department of Energy. 1982. Nuclear Safety Criteria and Specifications for Space Nuclear Reactors. OSNP-1, Rev. 0, Aug.